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Mangrove carbon stocks and biomass partitioning in an extreme environment

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ABSTRACT

Global inventories that show mangrove forests have rich carbon stores currently lack data from arid areas where carbon stocks may be functionally impoverished relative to humid regions. We quantified total carbon stocks (C) of three arid *Avicennia marina* stands in Qatar and report an aboveground biomass allometric equation and the first below ground biomass allometric equation in the region. The allometric relationships indicate that below ground mangrove C stocks in arid locations are more important than previously reported. Comparison of previously published and our locally developed allometric equations show that *A. marina* in Qatar allocate comparatively more biomass to below ground components than the same species in tropical humid settings, which is consistent with plant adaptations to living in stressed conditions. Total C stocks were 45.70 ± 3.70 Mg C ha⁻¹, of which tree and soil C stocks to 50 cm depth represented 10.18 ± 0.82 Mg C ha⁻¹ and 35.52 ± 2.88 Mg C ha⁻¹ respectively. Soil C stocks to 1 m depth were 50.17 ± 6.27 Mg C ha⁻¹. Overall, mangroves sustain relatively small C stocks in the arid, hypersaline environment of Qatar, which may be due to both relatively low tree productivity and growth, as well as limited rainfall-driven transport of terrigenous sediment inputs. By providing further estimates of mangrove carbon at their climatic extremes, these results can contribute to a better quantification of global mangrove carbon, reduce uncertainty in below ground tree C estimates from arid mangroves and have implications for mangrove carbon stocks in the face of climate change.

1. Introduction

Research over the past decade has shown that coastal wetlands, mangroves, salt marshes and seagrass beds represent significant global carbon sinks (Alongi, 2014; Donato et al., 2011; Fourqurean et al., 2012; Murdiyarso et al., 2015). Accumulated organic carbon (C) is stored in slowly decomposing, anoxic soils over long time-scales (Alongi, 2014), generating deep below-ground 'blue carbon' stores with greater per-area carbon stocks than tropical upland forests (Alongi, 2012; Donato et al., 2011; Fourqurean et al., 2012). Coastal wetlands are also of greater importance to ocean carbon dynamics than their relatively small area would suggest (Donato et al., 2011; Fourqurean et al., 2012). Among coastal wetlands, mangroves are particularly carbon rich; total tree and soil carbon stocks contain up to 1023 Mg C ha⁻¹ in the tropics, five times

that of the most productive seagrass beds (~200 Mg C ha⁻¹) and almost double that of saltmarshes (~600 Mg C ha⁻¹) (Alongi, 2014; Donato et al., 2011). Consequently, mangrove carbon-storage potential has attracted much scientific and political interest as a means of mitigating against greenhouse gas (GHG) emissions (Cameron et al., 2019; Donato et al., 2011; Fourqurean et al., 2012; Liu et al., 2014; Schile et al., 2017; Wang et al., 2013). While mangrove soil carbon accumulates over centuries, current rates of deforestation makes the soil vulnerable to oxidation, with significant risks of increased GHG emissions (Almahasheer et al., 2017; Donato et al., 2011; Ezcurra et al., 2016; Kauffman et al., 2017). Conservation and restoration programmes have been identified as a profitable means of curbing GHG emissions that is comparable to investment in traditional asset classes (Cameron et al., 2019), although the prevention of further loss is, by far, the most effective way

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of maintaining wetland carbon storage (Kauffman et al., 2017).

Carbon stocks in mangrove forests are mainly derived from estimates in the wet tropics, but there is limited emerging empirical data on how the ecological functioning of arid mangroves compares to that of their tropical humid counterparts (Almahasheer et al., 2017; Sanders et al., 2016; Schile et al., 2017). Annual rainfall and air temperature are important drivers of carbon stocks in tropical and sub-tropical mangroves (Rovai et al., 2018; Sanders et al., 2016). Increased rainfall is associated with higher mangrove productivity, which can become stored in the soil (Xiong et al., 2018). In China, up to 97% of carbon in the top 1 m has been found to be of mangrove origin (Xiong et al., 2018), though terrigenous sediment contributions may be higher where there is freshwater-mediated input from river catchments (Adame et al., 2010). In estuarine soils across a large geographical area, strong inverse relationships have been found between rainfall and salinity and positive relationships between precipitation, plant productivity and soil organic matter (Osland et al., 2018). Mangroves in the western Arabian/Persian Gulf (hereafter referred to as “the Gulf”) persist in very arid conditions, with rainfall as low as 54 mm yr⁻¹ (Price et al., 1993), compared to even the semi-arid mangroves of Senegal, where precipitation averages 650 mm yr⁻¹ (Kauffman and Bhomia, 2017) and with heightened salinity (~60, Practical Salinity Units) (Perri et al., 2018). Air temperatures are also extreme in the Gulf, ranging from 50 °C in the summer to below 0 °C in winter (Al-Khayat and Jones, 1999; Halwagy et al., 1982; Price et al., 1993; Sheppard et al., 2010), which likely limits northerly mangrove distribution of the Gulf. Recent studies indicate carbon stocks are low in arid and semi-arid mangroves, with averages of 218.4 Mg C ha⁻¹ in the United Arab Emirates (Schile et al., 2017) and 463 Mg C ha⁻¹ in Senegal in soils deeper than 1 m. However, carbon stocks are not universally impoverished in arid regions - soil carbon can reach up to 1130 Mg C ha⁻¹ in arid parts of Baja California from cores up to 2 m depth (Ezcurra et al., 2016).

Tropical humid mangroves can hold a significant proportion of their carbon stocks in above and below ground biomass (Donato et al., 2011; Kauffman et al., 2011), often estimated from species-specific allometric equations (Komiyama et al., 2008). Relatively little work has investigated allometric equations of mangroves in arid regions, particularly the Gulf. Schile et al. (2017) applied an *Avicennia marina* allometric equation from a tropical humid area of Australia to estimate tree carbon pools in the arid environment of the United Arab Emirates. There is also a lack of below ground biomass allometric equations, due to the logistical difficulties involved in sampling and accurately estimating mangrove root material (Komiyama et al., 2008). Many previous efforts have used either generic allometric models or equations developed in different climatic settings in estimating below ground biomass and carbon stocks (Hamilton and Friess, 2018; Hutchison et al., 2014; Schile et al., 2017), which may not necessarily provide accurate estimates. Past research has shown tree growth morphology and mangrove carbon allocation can vary between species and across climatic gradients (Banerjee et al., 2013; Chave et al., 2005; Komiyama et al., 2005; Smith and Whelan, 2006). Under stressful conditions previous work has shown that mangroves boost below ground partitioning and increase root biomass, which may be associated with increased soil salinity (Sherman et al., 2003). Thus, arid mangroves may have lower shoot to root ratios, and proportionally greater below-ground carbon allocation than mangroves in higher rainfall, tropical humid locations.

The current study provides results that are relevant to other arid regions where mangroves occur, for example, western Australia, western Africa, western South America, north-western Mexico and the western Gulf of Mexico. These results can also add to our knowledge of C stocks globally by refining estimates in arid countries. This study reports an aboveground biomass allometric equation and the first below ground biomass allometric equation for *A. marina* in the Gulf. This will add insight to the hypothesis that arid mangroves allocate more biomass below ground and will help reduce uncertainty in arid environment estimates. The study also aimed to develop and test regionally driven

differences in above and below ground *Avicennia marina* allometric relationships.

2. Methods

Study Sites: Three mangrove sites were selected for study on the north east coast of Qatar (N 25.726251°, E 51.565021°, Fig. 1). Salinity can be highly variable, ranging from 37 to 64 in a lagoonal setting (Al-Maslamani et al., 2013; Perri et al., 2018). Despite low annual precipitation, no incidents of drought-induced mortality, expansion or contraction in response to rainfall have been reported. Intertidal areas where sampling sites were located were dominated by mangroves. Sites were fringed by seagrass beds on the seaward side and, on the terrestrial side, by sabkha (supra-tidal salt flats vegetated with nonvascular halophytes) and microbial mat habitats, above which was a rocky desert landscape. Mangroves in Qatar are monospecific *Avicennia marina* stands. All stands occur along the eastern and northern coasts, with just a few isolated *A. marina* trees on the western coast. Sites around Al Khor and Al Dhakira bays were selected for study as they represent ~80% of total mangrove area in Qatar (Al-Khayat and Balakrishnan, 2014) and cover ~680 ha, providing a large enough area to study effects of tidal gradients throughout the mangroves. The Al Khor site was in the northern part of Al Khor bay and 4 km from Al Khor town. South and West Al Dhakira sites were situated in southern and western portions of Al Dhakira bay respectively and were separated by 3 km of sandy beach.

Sampling design: Mangrove sites were sampled by nine 10 × 10 m plots in three zones (Fig. S1a): three plots along the seaward and landward fringes, respectively, and three plots in the mid-mangrove that were placed at roughly equal distances along a transect running perpendicular to the shoreline. Collectively, plot distribution sampled the effect of the intertidal gradient on carbon stocks, while leaving scope for factorial contrasts between the low (n = 3 plots), mid (n = 3) and high (n = 3) mangrove stands. Each plot was marked using a handheld GPS and distance to the seaward edge and each transect length were measured *a priori* in Google earth. Transect lengths were, 2500m, 990m and 1250m in Al Khor, South Dhakira and West Dhakira, respectively. Tidal ranges in Qatar are microtidal, <2m with a mean high water of circa 1.5m, with a relative height difference of approximately 0.7m between the low to high stations within the mangrove.

Field and laboratory methods: Above and below-ground carbon stocks of mangrove trees are normally estimated from empirically-determined allometric relationships between tree dry mass and tree diameter at breast height (DBH) (Clough et al., 1997). DBH is not a good predictor of dry mass for arid countries, such as Qatar, where trees branch low to the ground and form multi-stemmed, bushy growths (Clough et al., 1997). Here, tree crown diameter (CD) and tree height were used instead of DBH for biomass and carbon allometry analysis (see below), as used by Clough et al. (1997) and Parvareesh et al. (2012) for multi-stemmed trees (Clough et al., 1997). All trees in each plot were measured for height, the diameter across the widest part of the canopy (Crown Length: CL) and the canopy diameter perpendicular to CL (Crown Width: CW). Crown Diameter (CD) was calculated as (CL + CW)/2. Below ground, the mass of large roots (>20 mm diameter) were estimated after establishing allometric equations (see below). The mass of fine roots (1–20 mm) (Sherman et al., 2003) was sampled using four 4.5 cm diameter 60 cm deep cores per plot (Alongi et al., 2000). Soil depth profile throughout the sites comprised an organic rich fine-root layer (ranging from 0 to <20 cm depth), below which was a homogenous soil layer to bedrock. The fine-root layer was a clearly visible horizon (Table 2). The depth of the fine-root layer was measured in four cores per plot. The contents of all cores were washed and sieved to 1 mm and all fine root material was dried to constant weight (60 °C for 48 h). Soil depth was observed at each plot by inserting a steel pole to the bedrock. To estimate dry bulk density (DBD) and organic carbon content, a hole was dug and two 5.5 cm diameter 3 cm deep cores were inserted horizontally into the soil, one to represent the fine root layer at <20 cm depth, the other at >30 cm

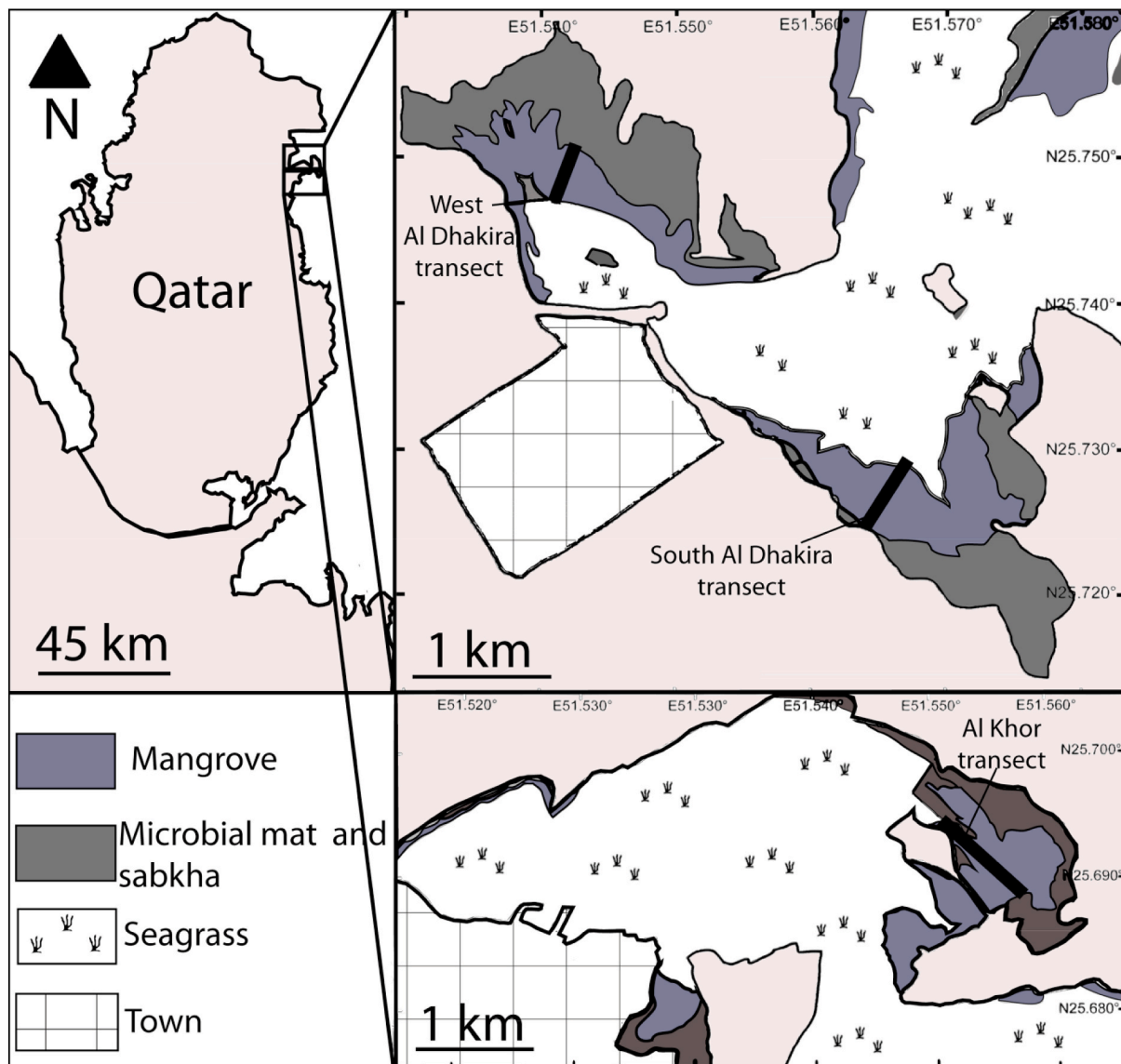


Fig. 1. Qatari *A. marina* sampling sites. Al Khor and Al Dhakira bays with mangrove transect locations marked.

depth (Mizanur Rahman et al., 2015) (Fig. S1b). Rather than sampling the whole depth range of the soil, subsamples were taken to represent a particular depth range as this strategy has been found to be adequate for mangroves where carbon content generally changes slowly with depth (Kauffman and Donato, 2012). Samples were dried to constant weight at 60 °C for 48 h and weighed to obtain DBD. Soil organic matter content was determined by loss on ignition (LOI) where samples were placed in a blast furnace at 400 °C for 16 h (Kauffman and Donato, 2012) and converted to organic soil carbon content (hereafter referred to as soil C as wt%) using a recently published conversion equation ($0.21\text{LOI}^{1.12}$, $R^2 = 0.86$) (Ouyang and Lee, 2020), which used 844 data points from 53 countries and included data from arid mangrove settings including the adjacent United Arab Emirates. Soil C density (mg C cm^{-3}) was calculated as $(\text{DBD (g cm}^{-3}) \times (\% \text{C}/100)) \times 1000$.

Tree excavation to establish allometric equations: Allometric relationships were established using 17 excavated trees designated for destruction by a coastal infrastructure project located in a bay 70 km south of the study sites (N 25.027395°, E 51.614390°). These mangroves were in a similar habitat to the study sites: sandy sediment and located adjacent to saltmarshes and seagrass beds. Isolated trees were selected to ensure that cable root material around the tree only originated from that tree (Matsui, 1998). Tree height (H), CL and CW were measured prior to

excavation. Trees were marked at ground level before excavation to allow later separation of above and below ground biomass. The ground was excavated to 0.5 m depth (Komiya et al., 2000), including the area falling below the canopy of each tree, plus 0.5 m radius beyond the edge of the canopy. This method provides a best estimate of below-ground biomass, as the excavation plot is proportional to the canopy size; it is superior to excavating in a constant 2 m radius for all excavated trees, irrespective of tree size (Comley and McGuinness, 2005). The mass of removed trees was divided into leaf, branch, stem and below-ground large root materials (>20 mm), and the dry weight of each component was established after drying at 60 °C for 48 h.

Converting Field Observations into Tree Carbon Stocks: The derived allometric equations were used at our study sites to convert CD measurements from plots to mean tree aboveground biomass (AGB) and large root (>20 mm) biomass ha^{-1} . Fine-root biomass (1–20 mm) obtained from plot cores was added to the large root biomass to obtain the below ground biomass (BGB) per plot. Biomass was converted to above and below ground tree carbon (onwards referred to as C_{AG} and C_{BG}) using 48% and 39% carbon content conversion, respectively (Kauffman and Donato, 2012). Measurements of soil C stocks are reported from soil depths that ranged from 16.25 to >200 cm depth. We standardised soil C stocks to a maximum 50 cm depth when sites were deeper than 50 cm.

When sites were shallower than 50 cm we calculated soil C stocks to bedrock to avoid overestimation of soil C stocks. To make comparisons with other reported stocks in the literature we also calculated stocks to 1 m depth. Out of our 27 soil cores, 15 were at least 50 cm and 7 were >1 m depth. The calculation was made by extrapolating the deeper soil layer to a total soil depth of 50 cm or 1 m by assuming that the deeper root-layer had constant soil properties (BD and %C) from 30 cm depth to 1 m. This method may lead to under or over-estimation of soil C stocks in deeper soils as %C may change with depth (Kauffman and Donato, 2012). Soil carbon stocks to 50 cm (C_{50}) and 1 m (C_{100}) depth for each mangrove plot was calculated as:

Soil C_{50} stocks (Mg C ha^{-1}) = ((Fine-root layer DBD (g cm^{-3}) x depth (cm) x (%C / 100)) + ((Deeper soil layer DBD (g cm^{-3}) x (50 – Fine-root layer depth) (cm) x (%C / 100)). (Kauffman and Donato et al., 2012)

Soil C_{100} stocks (Mg C ha^{-1}) = ((Fine-root layer DBD (g cm^{-3}) x depth (cm) x (%C / 100)) + ((Deeper soil layer DBD (g cm^{-3}) x (100 – Fine-root layer depth) (cm) x (%C / 100)). (Kauffman and Donato et al., 2012)

Statistical Analysis: Two-way Analysis of Variance (ANOVA) were used to test for effect of study sites (random factor, 3 levels) or mangrove zone (3 levels: high, mid and low mangrove) on Tree_{CD} and tree height. Linear regression was used to test for effect of distance to the seaward fringe on the responses of C_{AG} , C_{BG} and C_{50} . Log-transformations were used where required to comply with test assumptions. Significant ANOVAs were followed by Tukey honest significant differences (HSD) post hoc comparisons of treatments. Regression analysis was used to establish allometric relationships of tree above and below ground biomass with CD and H. A logarithmic transformation was used to linearize the relationship between variables and ensure homogeneity of variance in model residuals (Estrada et al., 2014). A high degree of collinearity was detected between crown diameter and tree height so multiple regression was not used. Comparison of R^2 and AIC, an estimate of the relative quality of statistical models, values was performed to determine the better predictor. After using allometric equations on log transformed data, the results were then back transformed for conversion to Mg ha^{-1} values for biomass estimation (Estrada et al., 2014).

To explore whether arid mangroves allocate proportionally more biomass below ground than mangroves in non-arid regions, we contrasted the allometric relationships of Qatari *A. marina* with those of other previously published work from two other regions: Iran (Parvaresh et al., 2012) and Australia (Comley and McGuinness, 2005). Both studies were used to compare aboveground biomass, while only the Australian study was used to compare below ground biomass. As Comley and McGuinness (2005) used DBH as a predictor of biomass, raw tree data measurements from Schile et al. (2017) were used to develop an equation to predict CD from DBH (Table 1 for equation and electronic supplement for data extracted from Schile et al., 2017). Analysis of Covariance (ANCOVA) was used to test for a difference between aboveground biomass and CD in different locations (factor: 3 levels) as well as below ground biomass between Qatar and Australia (factor: 2 levels). Log $x + 1$ transformations were used to comply with ANCOVA test assumptions.

Table 1

Allometric equations developed from tree removal and raw data from Schile et al. (2017). B = biomass (kg), CD = crown diameter (m), DBH = diameter at breast height (cm). *This equation was developed using raw data from Schile et al. (2017).

| Tree component | Equation | R^2 |
|-------------------------------|--|-------|
| Aboveground biomass | $\text{Log (AG)} = 2.14 \times \text{Log (CD)} + 0.20$ | 0.94 |
| Below ground biomass | $\text{Log (BG)} = 2.67 \times \text{Log (CD)} - 0.11$ | 0.89 |
| Leaf biomass | $\text{Log (B)} = 2.41 \times \text{Log (CD)} - 0.13$ | 0.88 |
| Branch and stem biomass | $\text{Log (B)} = 2.09 \times \text{Log (CD)} + 0.15$ | 0.89 |
| Convert DBH to crown diameter | $\text{CD} = 0.3831 \times \text{DBH} + 0.6863^*$ | 0.53 |

Table 2

Mean \pm st. error tree density, mean plot crown diameter (CD), tree height (H), below ground and aboveground biomasses (Mg ha^{-1}) and aboveground to below ground biomass ratio in different sites and intertidal depths in Qatar mangroves.

| Intertidal depth | Density trees ha^{-1} | CD (m) | H (m) | BGB Mg ha^{-1} | AGB Mg ha^{-1} | BGB ratio |
|------------------|--------------------------------|-----------------|-----------------|-------------------------|-------------------------|------------------|
| Al Khor | | | | | | |
| Low | 1433 \pm 190.52 | 2.04 \pm 0.15 | 1.98 \pm 0.07 | 10.55 \pm 1.83 | 11.99 \pm 2.00 | 0.47 \pm 0.007 |
| Mid | 3500 \pm 94.28 | 1.32 \pm 0.08 | 2.02 \pm 0.06 | 12.84 \pm 2.68 | 11.59 \pm 3.36 | 0.54 \pm 0.029 |
| High | 2100 \pm 374.17 | 1.25 \pm 0.04 | 1.41 \pm 0.04 | 7.47 \pm 2.17 | 7.19 \pm 2.23 | 0.51 \pm 0.010 |
| West Al Dhakira | | | | | | |
| Low | 1233 \pm 118.63 | 2.20 \pm 0.08 | 2.81 \pm 0.16 | 15.17 \pm 2.59 | 15.76 \pm 2.87 | 0.49 \pm 0.005 |
| Mid | 4700 \pm 1143.10 | 1.17 \pm 0.09 | 1.81 \pm 0.05 | 16.17 \pm 1.65 | 13.48 \pm 3.68 | 0.56 \pm 0.066 |
| High | 2767 \pm 427.74 | 1.39 \pm 0.12 | 1.65 \pm 0.06 | 14.68 \pm 2.45 | 5.80 \pm 0.87 | 0.72 \pm 0.006 |
| South Al Dhakira | | | | | | |
| Low | 1567 \pm 347.48 | 1.95 \pm 0.15 | 1.88 \pm 0.13 | 18.96 \pm 1.46 | 6.92 \pm 0.71 | 0.73 \pm 0.005 |
| Mid | 2933 \pm 54.43 | 1.47 \pm 0.09 | 2.07 \pm 0.07 | 21.21 \pm 3.04 | 6.89 \pm 1.03 | 0.76 \pm 0.009 |
| High | 3067 \pm 625.98 | 1.35 \pm 0.10 | 1.54 \pm 0.03 | 13.77 \pm 1.18 | 4.89 \pm 0.18 | 0.74 \pm 0.017 |

3. Results

Stand Characteristics of Qatar Mangroves: Mean \pm standard error (s.e. m) tree density, crown diameter (CD) and tree height (H) were 2589 ± 267 trees ha^{-1} , 1.57 ± 0.08 m and 1.92 ± 0.09 m, respectively (Table 2). Trees excavated for use in allometric models had mean CD and H of 1.18 ± 0.10 m and 1.03 ± 0.67 m respectively. Site and mangrove zone had interactive effects on CD (ANOVA: $F_{4, 691} = 5.03$, $p < 0.01$) and height (ANOVA: $F_{4, 691} = 16.02$, $p < 0.01$, $p < 0.01$). A greater CD was generally associated with low tidal zones and the tallest trees were in West Al Dhakira. Shorter trees were found in high tidal areas, particularly in Al Khor. Tree biomass was fairly low (overall average: 23.93 ± 1.39 Mg ha^{-1}) and substantially greater below ground (14.54 ± 0.98 Mg ha^{-1}) than aboveground (9.39 ± 0.94 Mg ha^{-1}), with below ground biomass ratio averaging 0.61 ± 0.02 .

Tree Allometry: Crown Diameter (CD) was a better predictor than tree height (H) for all tree components. Subsequently, only CD was used as a predictor in allometric equations (Table 1). The relationship between aboveground biomass and CD varied between global locations. With increase in size (CD), Australian trees grew proportionally more aboveground and below ground biomass than Qatari trees, however, Qatari trees had a steeper above and below ground biomass increase with size than Australian trees. ANCOVA confirmed these differences between Australia, Qatar and Iran aboveground (ANCOVA: $F_{5,32} = 51.63$, $p < 0.01$, Fig. 2a) and below ground biomass (ANCOVA: $F_{3,25} = 194.7$, $p < 0.01$, Fig. 2b).

Tree and Soil Carbon stocks: Across all sites, wood biomass contained a mean carbon content (C) of $10.18 (\pm 0.82)$ Mg C ha^{-1} . Of that, mean above and below ground tree C were 4.51 Mg ha^{-1} (± 0.44) and 5.67 Mg ha^{-1} (± 0.38), respectively. Distance to the seaward edge had a significant effect on overall tree C (Regression: $F_{1,25} = 7.34$, $p = 0.01$). Aboveground C did not vary with distance to the seaward edge (Regression: $F_{1, 25} = 2.74$, $p = 0.11$, Fig. 3a). However, below ground tree C was inversely related to distance to the seaward edge (Regression: $F_{1,25} = 6.85$, $p = 0.01$, Fig. 3b). Across all tidal heights, tree stocks accounted for 23.98% of total carbon (C_{TOT}) (Fig. 4). Overall mean total stocks were 45.70 ± 3.70 Mg C ha^{-1} . Soil C_{50} were 30.48 ± 5.11 , 44.39 ± 5.63 and 31.69 ± 3.39 Mg ha^{-1} in low, mid and high tidal zones respectively. When extrapolated to 1m depth, overall mean soil C_{100} stocks were 50.17 ± 6.27 Mg C ha^{-1} . There was no significant effect of

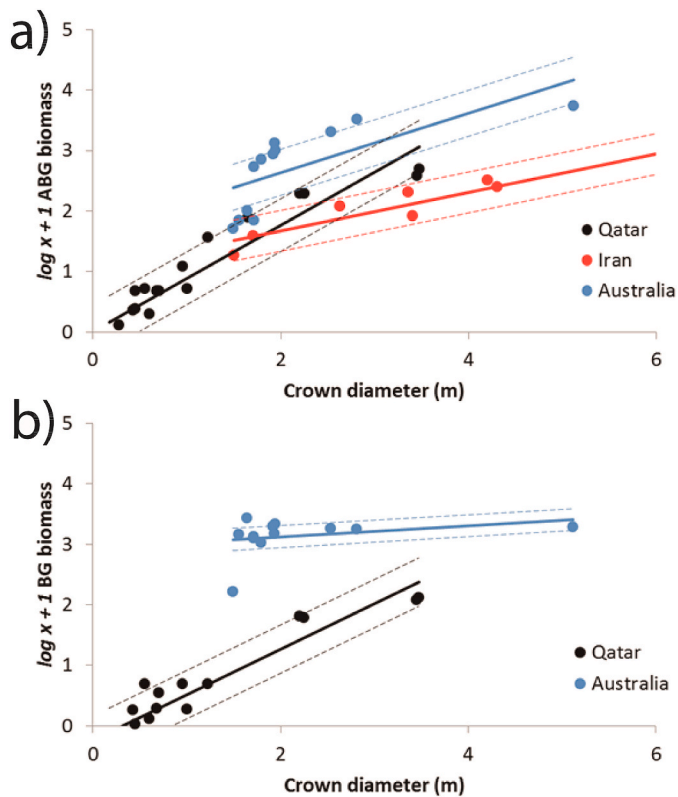


Fig. 2. Allometric relationships of a) aboveground and b) below ground biomass with crown diameter for *A. marina* trees of three global locations. Australia data were from Connolly and McGuinness (2005), Iran data from Parvaresh et al. (2012). Solid and dashed lines represent mean and 95% CI's colour coded for each location.

distance to the seaward edge on soil C_{50} (Regression: $F_{1,25} = 0.45$, $p = 0.51$). Carbon density was significantly higher in the fine root layer closer to the sediment surface than in the soil below the fine-root layer (ANOVA: $F_{1,52} = 27.46$, $p < 0.01$). Mean soil C density across all sites in the fine root layer was $11.81 \pm 1.49 \text{ mg cm}^{-3}$, compared to $6.98 \pm 0.74 \text{ mg cm}^{-3}$ in deeper soil (Table 3). Mean BD was $1.18 \pm 0.13 \text{ g cm}^{-3}$ and %C was $1.51 \pm 0.35\%$, as a result, overall mean soil C density was $9.40 \pm 0.66 \text{ mg cm}^{-3}$. Soil C in the mid mangroves were characterised by comparatively low BD ($0.82 \pm 0.07 \text{ g cm}^{-3}$) and high %C (2.73 ± 0.37), whereas, high and low mangroves had higher BD (high = $1.35 \pm 0.07 \text{ g cm}^{-3}$; low = $1.36 \pm 0.05 \text{ g cm}^{-3}$) and lower %C (high = 1.19 ± 0.29 ; low = 0.62 ± 0.04).

4. Discussion

This study is in agreement with recent findings, which report lower overall C stocks for the arid mangroves of the Arabian Peninsula compared to global averages. Mangrove C stock extrapolated to 1 m depth in Qatar ($50.17 \pm 6.27 \text{ Mg C ha}^{-1}$) are comparable to 43–76 Mg C ha^{-1} in 1 m depth soil reported from the Red Sea to the Gulf (Almahsheer et al., 2017; Cusack et al., 2018). However, these results are much lower than 728–1363 Mg C ha^{-1} reported throughout the tropics to comparable depths (Alongi, 2012; Gress et al., 2017; Kauffman et al., 2011; Murdiyarso et al., 2015). Mean above and below ground tree C stocks ($C_{AG} = 4.51 \pm 0.44 \text{ Mg ha}^{-1}$ and $C_{BG} = 5.67 \pm 0.38 \text{ Mg ha}^{-1}$) and tree sizes ($CD = 1.57 \pm 0.10$ and $H = 1.86 \pm 0.03$) were comparable to other arid regions in which mangroves occur. Mean tree C stocks of $27.50 \text{ Mg C ha}^{-1}$, of *A. marina* in the Gulf, and $47.5 \text{ Mg C ha}^{-1}$, in arid mangroves of West Africa, have been reported (Kauffman and Bhomia, 2017; Schile et al., 2017). Across the UAE, Schile et al. (2017) found an inverse relationship in mangrove tree C stocks with distance from the

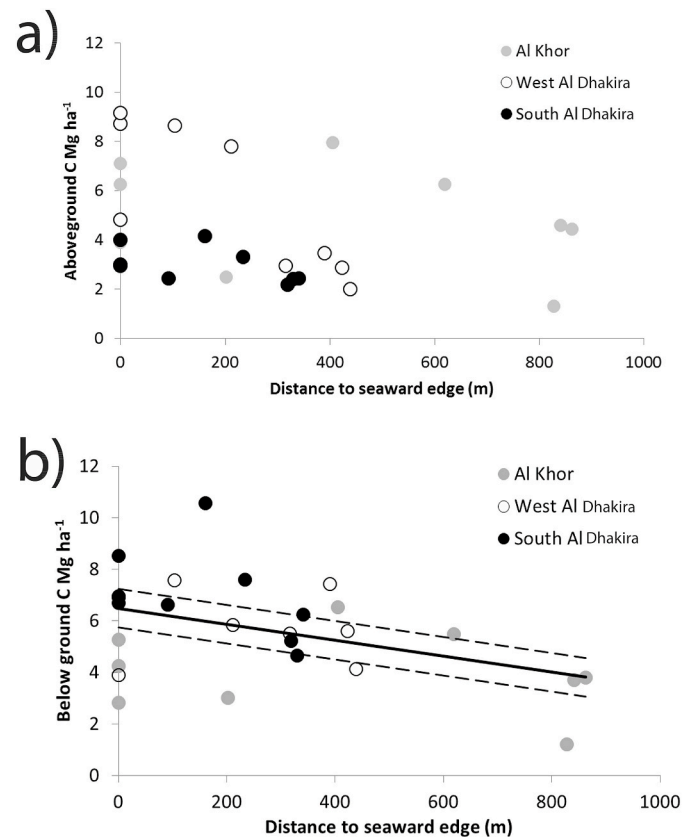


Fig. 3. a) aboveground and b) below ground tree C distance to seaward edge in the three different mangrove sampling locations. Black solid lines and dashed lines represent overall mean and 95% CI's respectively.

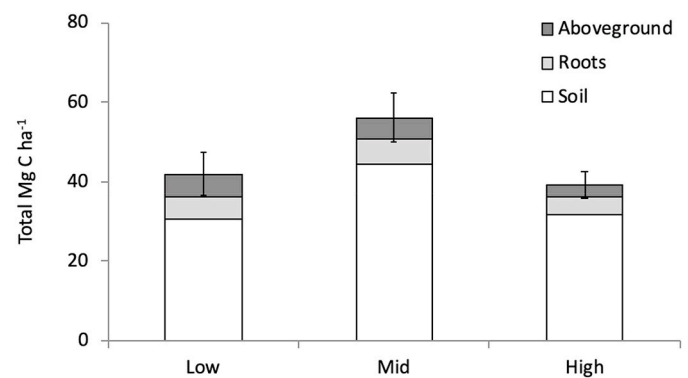


Fig. 4. Total C across tidal zones in Qatari mangroves. Mean \pm SEM aboveground, root and soil carbon stocks across the three mangrove shore heights, at three sites in Qatar.

mouth of the Gulf and attributed this effect to increases in salinity. In the UAE tree C stocks ranged from $147.50 \text{ Mg C ha}^{-1}$ at the entrance of the Gulf to $29.46 \text{ Mg C ha}^{-1}$ at their most western sampling location (Schile et al., 2017). These estimates are considerably lower than those reported from other tropical humid regions where total tree C stocks have been reported up to 10 times greater (Alongi, 2012; Donato et al., 2012; Kauffman et al., 2011). *A. marina* in Qatar were much smaller than 7–10 m height and 3–6 m CD of the same species in tropical locations (Komiya et al., 2008; Suhardiman et al., 2016). Higher salinities in Qatar (34–67) (Al-Maslami et al., 2013; Perri et al., 2018), compared to 4–36 in tropical locations (Chowdhury et al., 2019; Pestana et al., 2017), could be limiting tree biomass and productivity, subsequently

Table 3

Mean \pm st. error fine root and deeper soil layer depths (cm), depth to bedrock (cm), bulk density (g cm^{-3}), carbon content (%), carbon density (mg C cm^{-3}) and soil carbon pools ($\text{Mg C}_{50} \text{ ha}^{-1}$) of sampled plots in Qatari mangroves. * these sampling locations had soil depths deeper than 50 cm, however, all measurements were standardised to 50 cm depth.

| Intertidal Depth | Soil Interval | Soil layer depth (cm) | Soil Depth (cm) | Bulk Density g cm ⁻³ | Carbon content % | C density mg cm ⁻³ | Interval soil C Mg ha ⁻¹ | Soil C ₅₀ Mg ha ⁻¹ |
|------------------|---------------|-----------------------|-----------------|---------------------------------|------------------|-------------------------------|-------------------------------------|--|
| Al Khor | | | | | | | | |
| Low | Fine-root | 8.82 ± 0.50 | 43.33 ± 3.56 | 1.36 ± 0.05 | 0.52 ± 0.05 | 7.03 ± 0.52 | 6.23 ± 0.67 | 24.31 ± 4.26 |
| | Deeper | 34.51 ± 3.97 | | 2.00 ± 0.05 | 0.26 ± 0.04 | 5.17 ± 0.74 | 18.08 ± 4 | |
| Mid | Fine-root | 9.23 ± 0.12 | 50.00 ± 0.00* | 0.43 ± 0.12 | 2.72 ± 0.65 | 10.06 ± 1.32 | 9.31 ± 1.3 | 39.42 ± 2.79 |
| | Deeper | 40.77 ± 0.12 | | 1.44 ± 0.17 | 0.52 ± 0.04 | 7.38 ± 0.69 | 30.1 ± 2.89 | |
| High | Fine-root | 8.00 ± 0.00 | 50.00 ± 0.00* | 1.15 ± 0.32 | 0.99 ± 0.29 | 9.58 ± 0.65 | 7.66 ± 0.52 | 30.94 ± 2.76 |
| | Deeper | 42.00 ± 0.00 | | 1.88 ± 0.20 | 0.3 ± 0.04 | 5.54 ± 0.61 | 23.28 ± 2.56 | |
| West Dhakira | | | | | | | | |
| Low | Fine-root | 12.88 ± 2.13 | 50.00 ± 0.00* | 0.94 ± 0.02 | 1.17 ± 0.01 | 11.03 ± 0.39 | 14.2 ± 2.33 | 46.85 ± 6.29 |
| | Deeper | 37.12 ± 2.13 | | 1.30 ± 0.13 | 0.65 ± 0.09 | 8.62 ± 1.79 | 32.65 ± 7.98 | |
| Mid | Fine-root | 14.49 ± 0.02 | 49.00 ± 0.82 | 0.35 ± 0.03 | 6.9 ± 1.5 | 23.27 ± 3.52 | 33.74 ± 5.16 | 64.72 ± 5.69 |
| | Deeper | 34.51 ± 0.98 | | 1.16 ± 0.14 | 0.79 ± 0.09 | 8.97 ± 0.29 | 30.97 ± 1.59 | |
| High | Fine-root | 11.44 ± 0.87 | 50.00 ± 0.00* | 1.45 ± 0.21 | 0.75 ± 0.14 | 10.27 ± 0.24 | 11.73 ± 0.73 | 41.29 ± 5.65 |
| | Deeper | 38.56 ± 0.87 | | 1.44 ± 0.17 | 0.52 ± 0.04 | 7.6 ± 1.48 | 29.56 ± 6.37 | |
| South Dhakira | | | | | | | | |
| Low | Fine-root | 15.36 ± 4.20 | 29.25 ± 10.49 | 1.13 ± 0.13 | 0.7 ± 0.09 | 7.64 ± 0.02 | 11.72 ± 3.17 | 20.28 ± 7.14 |
| | Deeper | 13.89 ± 6.39 | | 1.46 ± 0.11 | 0.43 ± 0.04 | 6.19 ± 0.25 | 8.56 ± 4.01 | |
| Mid | Fine-root | 10.64 ± 0.52 | 38.75 ± 2.50 | 0.22 ± 0.02 | 4.97 ± 0.29 | 10.94 ± 1.88 | 11.45 ± 1.45 | 29.03 ± 1.88 |
| | Deeper | 28.11 ± 2.63 | | 1.33 ± 0.017 | 0.47 ± 0.01 | 6.26 ± 0.08 | 17.57 ± 1.43 | |
| High | Fine-root | 8.25 ± 0.73 | 21.67 ± 2.68 | 0.76 ± 0.30 | 4.05 ± 2.74 | 16.48 ± 4.91 | 13.76 ± 4.24 | 22.84 ± 3.60 |
| | Deeper | 13.41 ± 3.29 | | 1.44 ± 0.17 | 0.52 ± 0.12 | 7.12 ± 0.77 | 9.08 ± 1.17 | |

reducing locally derived carbon inputs. In coastal wetlands, Osland et al. (2018) found strong associations between rainfall, salinity, productivity and soil organic matter, where increased precipitation was linked to lower salinity, increased productivity and increased soil organic matter.

The values reported by the current study further support the contention that mangroves in low-rainfall, hypersaline areas have a limited capacity for carbon storage, as recently suggested (Almahasheer et al., 2017; Sanders et al., 2016; Schile et al., 2017). The current study found lower BD and %C than tropical humid areas where BD and %C range from 0.19 to 0.92 g cm^{-3} and 1.74 – 26.3% respectively, as a result, soil C density in Qatar is up to a tenth of soil C densities reported in the tropics where they can reach 152 mg C cm^{-3} (Rovai et al., 2018). Carbon stores in mangrove soils are largely attributed to autochthonous mangrove inputs, through tree biomass material being deposited in soils (Almahasheer et al., 2017; Saintilan et al., 2013; Xiong et al., 2018). As mangrove productivity is reduced in arid settings (Cintron et al., 1978), the amount of locally derived mangrove material available for soils is also reduced (Saintilan et al., 2013). Low rainfall also restricts riverine and runoff input of allochthonous carbon to mangroves (Saintilan et al., 2013; Xiong et al., 2018). Walton et al. (2014) estimated that 60–80% of organic material in sediments at the sites investigated in this study (Al-Khor and Al-Dhakira) originated from mangroves, with the balance accounted for by inwelling of allochthonous material from seagrass and coastal planktonic sources.

In Qatar, within stand tree distribution differed from tropical humid areas, smaller trees were found on the landward edge than the rest of the stand (Donato et al., 2011; Kauffman et al., 2011), which may reflect the nutrient-poor habitat in which *A. marina* are found in the Gulf. These results provide insight into the nutrient dynamics of arid mangroves and are comparable to Western Australia where mangroves nitrogen decreases in a seaward to landward direction (Adame et al., 2020). Mangroves in humid conditions can be highly productive outwelling systems, dependant on their geomorphological setting (Lee, 1995) but the relative importance of outwelling and inwelling processes are much less well understood in arid mangroves. Emerging research shows inwelling of material from the sea can be important in arid mangroves (Al-Maslamani et al., 2013; Walton et al., 2014). In Qatari mangroves seagrass production has been shown to be a contributor to both food webs supporting mangrove-resident fauna (Al-Maslamani et al., 2013) and soil within mangroves (Al-Maslamani et al., 2013; Walton et al.,

2014), with the greatest input to soils at the mangrove fringe, indicating potential higher nutrient availability for seaward as opposed to landward trees.

Differences were found in allometric growth relationships developed by the present study and those developed in other areas. Below ground biomass of Qatari mangroves had a steeper biomass increase with increasing crown diameter (CD) when compared to *A. marina* from a tropical humid area of Australia (Comley and McGuinness, 2005). Additionally, the relationship between aboveground biomass and CD in *A. marina* derived from Iran was more like that of Australia. Interestingly, the study site used to develop an *A. marina* allometric equation in Iran was on the coast of the Oman Sea, and the location where mangroves were sampled receives freshwater runoff and is considered biologically separated from the Gulf (Price et al., 1993). This environmental setting may be why the relationship in Iran was more like tropical humid Australian mangroves than of the geographically adjacent Qatari mangroves. The below ground biomass ratio recorded here (0.61) is higher than that reported anywhere else (0.1–0.55) for *Avicennia* trees (Alongi and Dixon, 2000; Kristensen et al., 2008; Matsui, 1998) and support the principle that mangrove trees boost energy allocation to below ground biomass when environmental conditions are stressful, for example under reduced rainfall or increased salinity (Adame et al., 2020, 2014; Asbridge et al., 2015; Duke et al., 2019; Lovelock, 2008; Lovelock et al., 2016). Relatively high below ground biomass ratios of up to 0.67 and 0.77 have been recorded for *Rhizophora* spp. dominated stands, although these were estimated from allometric equations that were not species-specific (Kauffman et al., 2011; Komiya et al., 2005). *Avicennia germinans* has shown a similar pattern of increasing below ground biomass from tropical to sub-tropical climates (Day et al., 1987; Fromard et al., 1998; Smith and Whelan, 2006). This previous work coupled with our present results indicate that previous predictive studies of above and below ground mangrove tree C stocks need to take into account regional differences in growth patterns to reduce uncertainty in their estimates. Our findings imply that previous studies may underestimate below ground mangrove tree C in arid or extreme environments by using equations developed in less harsh environments. For example, Bhomia and Kauffman (Kauffman and Bhomia, 2017) and Banerjee et al. (2013) found an inverse relationship of biomass with soil salinity and developed different allometric equations based on salinity zones in Bangladesh.

The current study further supports the previous indications that

mangroves in low-rainfall, hypersaline areas have a limited capacity for carbon storage (Almahasheer et al., 2017; Sanders et al., 2016; Schile et al., 2017). The allometric equations developed here show that mangroves in Qatar have a greater increase in below ground biomass relative to tree size than other less extreme environments. The study also found mangrove height was lower and crown diameter smaller in Qatar than other regions, which accounts for the comparatively low aboveground tree C stocks. Within-stand mangrove distribution showed an inverse relationship between density and distance to the seaward fringe, which contrasts with other regions and suggests differing nutrient dynamics in arid mangrove systems. Allometric equations presented here can reduce uncertainty in below ground biomass and C estimates for mangroves in arid regions and also implies that previous work from these locations may have underestimated below ground mangrove C stocks, an important component of carbon storage in mangroves. These results have implications for mangroves in the face of climate change: as mangroves are expanding their distribution pole-ward into temperate and sub-tropical regions (Osland et al., 2017; Saintilan et al., 2014), mangrove ecosystems on the edge of their global distribution are likely to become more expansive and widespread. Precipitation regimes across the sub-tropics are projected to increase and decrease (Sillmann et al., 2013). In areas where precipitation declines, carbon storage may be significantly reduced. As a result of reduced and less frequent precipitation, carbon impoverished arid mangroves are likely to become more common in the sub-tropics in the 21st century.

CRedit authorship contribution statement

Mark Chatting: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing - review & editing, Writing - original draft. **Lewis LeVay:** Conceptualization, Methodology, Investigation, Writing - review & editing, Writing - original draft, Supervision, Project administration, Funding acquisition. **Mark Walton:** Conceptualization, Methodology, Investigation, Writing - review & editing, Writing - original draft, Supervision, Project administration, Funding acquisition. **Martin W. Skov:** Conceptualization, Methodology, Investigation, Writing - review & editing, Writing - original draft, Supervision, Project administration, Funding acquisition. **Hilary Kennedy:** Writing - review & editing, Writing - original draft, Supervision, Project administration, Funding acquisition. **Simon Wilson:** Writing - review & editing, Writing - original draft. **Ibrahim Al-Maslamani:** Investigation, Supervision, Project administration, Funding acquisition, Writing - review & editing, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecss.2020.106940>.

Data availability

All underlying data for this study is uploaded as an electronic supplement.

References

- Adame, M.F., Neil, D., Wright, S.F., Lovelock, C.E., 2010. Sedimentation within and among mangrove forests along a gradient of geomorphological settings. *Estuar. Coast. Shelf Sci.* 86, 21–30. <https://doi.org/10.1016/j.ecss.2009.10.013>.
- Adame, M.F., Reef, R., Santini, N.S., Najera, E., Turschwell, M.P., Hayes, M.A., Masque, P., Lovelock, C.E., 2020. Mangroves in arid regions: ecology, threats, and opportunities. *Estuar. Coast. Shelf Sci.* <https://doi.org/10.1016/j.ecss.2020.106796>.
- Adame, M.F., Teutli, C., Santini, N.S., Caamal, J.P., Zaldívar-Jiménez, A., Herrández, R., Herrera-Silveira, J.A., 2014. Root biomass and production of mangroves surrounding a karstic oligotrophic coastal lagoon. *Wetlands* 34, 479–488. <https://doi.org/10.1007/s13157-014-0514-5>.
- Al-Khayat, J., Balakrishnan, P., 2014. *Avicennia marina* around Qatar: tree, seedling and pneumatophore densities in natural and planted mangroves using remote sensing. *Interm. J. Sci.* 3, 18–27.
- Al-Khayat, J.A., Jones, D.A., 1999. A comparison of the macrofauna of natural and replanted mangroves in Qatar. *Estuar. Coast. Shelf Sci.* 49, 55–63. [https://doi.org/10.1016/S0272-7714\(99\)80009-2](https://doi.org/10.1016/S0272-7714(99)80009-2).
- Al-Maslamani, I., Walton, M.E.M., Kennedy, H.A., Al-Mohannadi, M., Le Vay, L., 2013. Are mangroves in arid environments isolated systems? Life-history and evidence of dietary contribution from inwelling in a mangrove-resident shrimp species. *Estuar. Coast. Shelf Sci.* 124, 56–63. <https://doi.org/10.1016/j.ecss.2013.03.007>.
- Almahasheer, H., Serrano, O., Duarte, C.M., Arias-Ortiz, A., Masque, P., Irigoien, X., 2017. Low carbon sink capacity of Red Sea mangroves. *Sci. Rep.* 7, 9700. <https://doi.org/10.1038/s41598-017-10424-9>.
- Alongi, D., Dixon, P., 2000. Mangrove primary production and above-and belowground biomass in Sawi Bay, Southern Thailand. *Phuk* 38, 31–38.
- Alongi, D.M., 2014. Carbon cycling and storage in mangrove forests. *Ann. Rev. Mar. Sci.* 6, 195–219. <https://doi.org/10.1146/annurev-marine-010213-135020>.
- Alongi, D.M., 2012. Carbon sequestration in mangrove forests. *Carbon Manag.* 3, 313–322. <https://doi.org/10.4155/cmt.12.20>.
- Alongi, D.M., Tirendi, F., Clough, B.F., 2000. Below-ground decomposition of organic matter in forests of the mangroves *Rhizophora stylosa* and *Avicennia marina* along the arid coast of Western Australia. *Aquat. Bot.* 68, 97–122. [https://doi.org/10.1016/S0304-3770\(00\)00110-8](https://doi.org/10.1016/S0304-3770(00)00110-8).
- Asbridge, E., Lucas, R., Accad, A., Dowling, R., 2015. Mangrove response to environmental changes predicted under varying climates: case studies from Australia. *Curr. For. Reports* 1, 178–194. <https://doi.org/10.1007/s40725-015-0018-4>.
- Banerjee, K., Sengupta, K., Raha, A., Mitra, A., 2013. Salinity based allometric equations for biomass estimation of Sundarban mangroves. *Biomass Bioenergy* 56, 382–391. <https://doi.org/10.1016/j.biombioe.2013.05.010>.
- Cameron, C., Hutley, L.B., Friess, D.A., Brown, B., 2019. High greenhouse gas emissions mitigation benefits from mangrove rehabilitation in Sulawesi, Indonesia. *Ecosyst. Serv.* 40 <https://doi.org/10.1016/j.ecoser.2019.101035>.
- Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145, 87–99. <https://doi.org/10.1007/s00442-005-0100-x>.
- Chowdhury, R., Sutradhar, T., Begam, M.M., Mukherjee, C., Chatterjee, K., Basak, S.K., Ray, K., 2019. Effects of nutrient limitation, salinity increase, and associated stressors on mangrove forest cover, structure, and zonation across Indian Sundarbans. *Hydrobiologia* 842, 191–217. <https://doi.org/10.1007/s10750-019-04036-9>.
- Cintron, G., Lugo, A.E., Pool, D.J., Morris, G., 1978. Mangroves of arid environments in Puerto Rico and adjacent islands. *Biotropica* 10, 110. <https://doi.org/10.2307/2388013>.
- Clough, B.F., Dixon, P., Dalhaus, O., 1997. Allometric relationships for estimating biomass in multi-stemmed mangrove trees. *Aust. J. Bot.* 45, 1023–1031. <https://doi.org/10.1071/BT96075>.
- Comley, B.W.T., McGuinness, K.A., 2005. Above- and below-ground biomass, and allometry, of four common northern Australian mangroves. *Aust. J. Bot.* 53, 431–436. <https://doi.org/10.1071/BT04162>.
- Cusack, M., Saderne, V., Arias-Ortiz, A., Masqué, P., Krishnakumar, P.K., Rabaoui, L., Qurban, M.A., Qasem, A.M., Prihartato, P., Loughland, R.A., Elyas, A.A., Duarte, C.M., 2018. Organic carbon sequestration and storage in vegetated coastal habitats along the western coast of the Arabian Gulf. *Environ. Res. Lett.* 13 <https://doi.org/10.1088/1748-9326/aac899>.
- Day, J.E., Conner, W., Ley-Lou, F., Day, R.H., Navarro, A.M., 1987. The productivity and composition of mangrove forest, laguna de terminos, Mexico. *Aquat. Bot.* 27, 267–284.
- Donato, D.C., Kauffman, J.B., Mackenzie, R.A., Ainsworth, A., Pfleeger, A.Z., 2012. Whole-island carbon stocks in the tropical Pacific: implications for mangrove conservation and upland restoration. *J. Environ. Manag.* 97, 89–96. <https://doi.org/10.1016/j.jenvman.2011.12.004>.
- Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. *Nat. Geosci.* 4, 293–297. <https://doi.org/10.1038/ngeo1123>.

- Duke, N.C., Field, C., Mackenzie, J.R., Meynecke, J.O., Wood, A.L., 2019. Rainfall and its possible hysteresis effect on the proportional cover of tropical tidal-wetland mangroves and saltmarsh-saltpans. *Mar. Freshw. Res.* 70, 1047–1055. <https://doi.org/10.1017/MF18321>.
- Estrada, G.C.D., Soares, M.L.G., Santos, D.M.C., Fernandez, V., de Almeida, P.M.M., Estevam, M.R., de, M., Machado, M.R.O., 2014. Allometric models for aboveground biomass estimation of the mangrove *Avicennia schaueriana*. *Hydrobiologia* 734, 171–185. <https://doi.org/10.1007/s10750-014-1878-5>.
- Ezcurra, P., Ezcurra, E., Garcillán, P.P., Costa, M.T., Aburto-Oropeza, O., 2016. Coastal landforms and accumulation of mangrove peat increase carbon sequestration and storage. *Proc. Natl. Acad. Sci. Unit. States Am.* 113, 4404–4409. <https://doi.org/10.1073/pnas.1519774113>.
- Fourqurean, J.W., Duarte, C.M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M.A., Apostolaki, E.T., Kendrick, G.A., Krause-Jensen, D., McGlathery, K.J., Serrano, O., 2012. Seagrass ecosystems as a globally significant carbon stock. *Nat. Geosci.* 5, 505–509. <https://doi.org/10.1038/ngeo1477>.
- Fromard, F., Puig, H., Mougin, E., Marty, G., Betoulle, J.L., Cadamuro, L., 1998. Structure, above-ground biomass and dynamics of mangrove ecosystems: new data from French Guiana. *Oecologia* 115, 39–53. <https://doi.org/10.1007/s004420050489>.
- Gress, S., Huxham, M., Kairo, J., Mugi, L., 2017. Evaluating, predicting and mapping belowground carbon stores in Kenyan mangroves - gress - 2016 - global change biology - wiley online library. *Global Change* 23, 224–234.
- Halwagy, R., Moustafa, A.F., Kamel, S.M., 1982. On the ecology of the desert vegetation in Kuwait. *J. Arid Environ.* 5, 95–107. [https://doi.org/10.1016/s0140-1963\(18\)31543-x](https://doi.org/10.1016/s0140-1963(18)31543-x).
- Hamilton, S.E., Friess, D.A., 2018. Global carbon stocks and potential emissions due to mangrove deforestation from 2000 to 2012. *Nat. Clim. Change* 8, 240–244. <https://doi.org/10.1038/s41558-018-0090-4>.
- Hutchison, J., Manica, A., Swetnam, R., Balmford, A., Spalding, M., 2014. Predicting global patterns in mangrove forest biomass. *Conserv. Lett.* 7, 233–240. <https://doi.org/10.1111/cons.12060>.
- Kauffman, B.J., Arifanti, V.B., Hernández Trejo, H., del Carmen Jesús García, M., Norfolk, J., Cifuentes, M., Hadriyanto, D., Murdiyarso, D., 2017. The jumbo carbon footprint of a shrimp: carbon losses from mangrove deforestation. *Front. Ecol. Environ.* 15, 183–188. <https://doi.org/10.1002/fee.1482>.
- Kauffman, J., Donato, D., 2012. Protocols for the Measurement, Monitoring and Reporting of Structure, Biomass and Carbon Stocks in Mangrove Forests. Center for International Forestry, Bogor, Indonesia. <https://doi.org/10.17528/cifor/003749>.
- Kauffman, J.B., Bhomia, R.K., 2017. Ecosystem carbon stocks of mangroves across broad environmental gradients in West-Central Africa: global and regional comparisons. *PLoS One* 12, e0187749. <https://doi.org/10.1371/journal.pone.0187749>.
- Kauffman, J.B., Heider, C., Cole, T.G., Dwire, K.A., Donato, D.C., 2011. Ecosystem carbon stocks of micronesia mangrove forests. *Wetlands* 31, 343–352. <https://doi.org/10.1007/s13157-011-0148-9>.
- Komiyama, A., Havanond, S., Srisawatt, W., Mochida, Y., Fujimoto, K., Ohnishi, T., Ishihara, S., Miyagi, T., 2000. Top/root biomass ratio of a secondary mangrove (*Ceriops tagal* (Perr.) C.B. Rob.) forest. *For. Ecol. Manage.* 139, 127–134. [https://doi.org/10.1016/S0378-1127\(99\)00339-4](https://doi.org/10.1016/S0378-1127(99)00339-4).
- Komiyama, A., Ong, J., Pongpan, S., 2008. Allometry, biomass, and productivity of mangrove forests: a review. (Special Issue: mangrove ecology - applications in forestry and coastal zone management). *Aquat. Bot.* 89, 128–137. <https://doi.org/10.1016/j.aquabot.2007.12.006>.
- Komiyama, A., Pongpan, S., Kato, S., 2005. Common allometric equations for estimating the tree weight of mangroves. *J. Trop. Ecol.* 21, 471–477. <https://doi.org/10.1017/S0266467405002476>.
- Kristensen, E., Bouillon, S., Dittmar, T., Marchand, C., 2008. Organic carbon dynamics in mangrove ecosystems: a review. *Aquat. Bot.* 89, 201–219. <https://doi.org/10.1016/j.aquabot.2007.12.005>.
- Lee, S.Y., 1995. Mangrove outwelling: a review. *Hydrobiologia* 295, 203–212. <https://doi.org/10.1007/BF00029127>.
- Liu, H., Ren, H., Hui, D., Wang, W., Liao, B., Cao, Q., 2014. Carbon stocks and potential carbon storage in the mangrove forests of China. *J. Environ. Manag.* 133, 86–93. <https://doi.org/10.1016/j.jenvman.2013.11.037>.
- Lovelock, C.E., 2008. Soil respiration and belowground carbon allocation in mangrove forests. *Ecosystems* 11, 342–354. <https://doi.org/10.1007/s10021-008-9125-4>.
- Lovelock, C.E., Krauss, K.W., Osland, M.J., Reef, R., Ball, M.C., 2016. The physiology of mangrove trees with changing climate, pp. 149–179. https://doi.org/10.1007/978-3-319-27422-5_7.
- Matsui, N., 1998. Estimated stocks of organic carbon in mangrove roots and sediments in Hinchinbrook Channel, Australia. *Mangroves Salt Marshes* 2, 199–204. <https://doi.org/10.1023/A:100959909208>.
- Mizanur Rahman, M., Nabiul Islam Khan, M., Fazlul Hoque, A.K., Ahmed, I., 2015. Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones. *Wetl. Ecol. Manag.* 23, 269–283. <https://doi.org/10.1007/s11273-014-9379-x>.
- Murdiyarso, D., Purbopuspito, J., Kauffman, J.B., Warren, M.W., Sasmito, S.D., Donato, D.C., Manuri, S., Krisnawati, H., Taberima, S., Kurnianto, S., 2015. The potential of Indonesian mangrove forests for global climate change mitigation. *Nat. Clim. Change* 5, 1089–1092. <https://doi.org/10.1038/nclimate2734>.
- Osland, M.J., Feher, L.C., Griffith, K.T., Cavanaugh, K.C., Enwright, N.M., Day, R.H., Stagg, C.L., Krauss, K.W., Howard, R.J., Grace, J.B., Rogers, K., 2017. Climatic controls on the global distribution, abundance, and species richness of mangrove forests. *Ecol. Monogr.* 87, 341–359. <https://doi.org/10.1002/ecm.1248>.
- Osland, M.J., Gabler, C.A., Grace, J.B., Day, R.H., McCoy, M.L., McLeod, J.L., From, A.S., Enwright, N.M., Feher, L.C., Stagg, C.L., Hartley, S.B., 2018. Climate and plant controls on soil organic matter in coastal wetlands. *Global Change Biol.* 24, 5361–5379. <https://doi.org/10.1111/gcb.14376>.
- Ouyang, X., Lee, S.Y., 2020. Improved estimates on global carbon stock and carbon pools in tidal wetlands. *Nat. Commun.* 11. <https://doi.org/10.1038/s41467-019-14120-2>.
- Parvaresh, H., Parvaresh, E., Zahedi, G., 2012. Establishing allometric relationship using crown diameter for the estimation of above-ground biomass of grey mangrove, *Avicennia marina* (forsk.) vierh in mangrove forests of sirik, Iran. *J. Basic. Appl. Sci. Res.* 2, 1763–1769.
- Perri, E., Tucker, M.E., Slowakiewicz, M., Whitaker, F., Bowen, L., Perrotta, I.D., 2018. Carbonate and silicate biomineralization in a hypersaline microbial mat (Mesaieed sabkha, Qatar): roles of bacteria, extracellular polymeric substances and viruses. *Sedimentology* 65, 1213–1245. <https://doi.org/10.1111/sed.12419>.
- Pestana, D.F., Pülmans, N., Nordhaus, I., Diele, K., Zimmer, M., 2017. The influence of crab burrows on sediment salinity in a *Rhizophora*-dominated mangrove forest in North Brazil during the dry season. *Hydrobiologia* 803, 295–305. <https://doi.org/10.1007/s10750-017-3282-4>.
- Price, A.R.G., Sheppard, C.R.C., Roberts, C.M., 1993. The Gulf: its biological setting. *Mar. Pollut. Bull.* 27, 9–15. [https://doi.org/10.1016/0025-326X\(93\)90004-4](https://doi.org/10.1016/0025-326X(93)90004-4).
- Rovai, A.S., Twilley, R.R., Castañeda-Moya, E., Riul, P., Cifuentes-Jara, M., Manrow-Villalobos, M., Horta, P.A., Simonassi, J.C., Fonseca, A.L., Pagliosa, P.R., 2018. Global controls on carbon storage in mangrove soils. *Nat. Clim. Change* 8, 534–538. <https://doi.org/10.1038/s41558-018-0162-5>.
- Saintilan, N., Rogers, K., Mazumder, D., Woodroffe, C., 2013. Allochthonous and autochthonous contributions to carbon accumulation and carbon store in southeastern Australian coastal wetlands. *Estuar. Coast. Shelf Sci.* 128, 84–92. <https://doi.org/10.1016/j.ecss.2013.05.010>.
- Saintilan, N., Wilson, N.C., Rogers, K., Rajkaran, A., Krauss, K.W., 2014. Mangrove expansion and salt marsh decline at mangrove poleward limits. *Global Change Biol.* 20, 147–157. <https://doi.org/10.1111/gcb.12341>.
- Sanders, C.J., Maher, D.T., Tait, D.R., Williams, D., Holloway, C., Sipso, J.Z., Santos, I.R., 2016. Are global mangrove carbon stocks driven by rainfall? *J. Geophys. Res. Biogeosciences* 121, 2600–2609. <https://doi.org/10.1002/2016JG003510>.
- Schile, L.M., Kauffman, J.B., Crooks, S., Fourqurean, J.W., Glavan, J., Megonigal, J.P., 2017. Limits on carbon sequestration in arid blue carbon ecosystems. *Ecol. Appl.* 27, 859–874. <https://doi.org/10.1002/eap.1489>.
- Sheppard, C., Al-Husiani, M., Al-Jamali, F., Al-Yamani, F., Baldwin, R., Bishop, J., Benzon, F., Dutrieux, E., Dulvy, N.K., Durvasula, S.R.V., Jones, D.A., Loughland, R., Medio, D., Nithyanandan, M., Pilling, G.M., Polikarpov, I., Price, A.R.G., Purkis, S., Riegl, B., Saburova, M., Namin, K.S., Taylor, O., Wilson, S., Zainal, K., 2010. The Gulf: a young sea in decline. *Mar. Pollut. Bull.* 60, 13–38. <https://doi.org/10.1016/j.marpolbul.2009.10.017>.
- Sherman, R.E., Fahey, T.J., Martinez, P., 2003. Spatial patterns of biomass and aboveground net primary productivity in a mangrove ecosystem in the Dominican republic. *Ecosystems* 6, 384–398. <https://doi.org/10.1007/s10021-002-0191-8>.
- Sillmann, J., Kharin, V.V., Zwiers, F.W., Zhang, X., Bronaugh, D., 2013. Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *J. Geophys. Res. Atmos.* 118, 2473–2493. <https://doi.org/10.1002/jgrd.50188>.
- Smith, T.J., Whelan, K.R.T., 2006. Development of allometric relations for three mangrove species in South Florida for use in the Greater Everglades Ecosystem restoration. *Wetl. Ecol. Manag.* 14, 409–419. <https://doi.org/10.1007/s11273-005-6243-z>.
- Suhardiman, A., Tsuyuki, S., Setiawan, Y., 2016. Estimating mean tree crown diameter of mangrove stands using aerial photo. *Procedia Environ. Sci.* 33, 416–427. <https://doi.org/10.1016/j.proenv.2016.03.092>.
- Walton, M.E.M., Al-Maslami, I., Skov, M.W., Al-Shaikh, I., Al-Ansari, I.S., Kennedy, H.A., Le Vay, L., 2014. Outwelling from arid mangrove systems is sustained by inwelling of seagrass productivity. *Mar. Ecol. Prog. Ser.* 507, 125–137. <https://doi.org/10.3354/meps10827>.
- Wang, G., Guan, D., Peart, M.R., Chen, Y., Peng, Y., 2013. Ecosystem carbon stocks of mangrove forest in yingluo bay, guangdong province of south China. *For. Ecol. Manage.* 310, 539–546. <https://doi.org/10.1016/j.foreco.2013.08.045>.
- Xiong, Y., Liao, B., Wang, F., 2018. Mangrove vegetation enhances soil carbon storage primarily through in situ inputs rather than increasing allochthonous sediments. *Mar. Pollut. Bull.* 131, 378–385. <https://doi.org/10.1016/j.marpolbul.2018.04.043>.